

METHOD FOR CHANGING THE FREQUENCY FOR SAMPLING SONAR
WAVEFRONTS

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BACKGROUND OF THE INVENTION

Field of the Invention

10 The present invention relates to underwater acoustic hydrophone arrays. More particularly to a method for processing received underwater sonar waveforms to thereby raise the high frequency limit of the array.

Description of the Related Art

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The gathering of data in an acoustic environment by means of an array of electrically interconnected hydrophones is important for commercial and military purposes. Passive sonar arrays have been used for many years in applications such as geologic surveys and submarine detection and tracking. They are essentially an
20 assembly of hydrophones held together by a strength member and moved through water by a platform such as a ship or submarine to detect sound signals in the water. Such sensors are useful for detecting the position of underwater sonar target contacts. Towed arrays of hydrophones are long, continuous, neutrally buoyant hose lines, often several hundred meters long, which periodically contain
25 numerous hydrophone receivers. Typically, these elongated arrays have a number of hydrophone elements in modules or clusters, along with their associated electronics and control leads, contained within the hose-shaped structure that extends through the water. In order to gather data in an ocean environment, one

end of a linear hydrophone array is coupled to a navigating vessel. The principle advantages of the towed array are that it is separated from noise generated by the towing platform, allowing for improved detection of low source level signals, and that it can be constructed so that it is significantly longer than the towing
5 platform, allowing for detection of lower frequency signals and for better bearing accuracy.

The individual hydrophones cooperate or interact to provide a beam, which may be steered to determine the bearing from the array of various acoustic targets. The
10 hydrophones are connected to suitable electronics on the towing vessel which indicates the bearing of an identified underwater target. Exemplary towed arrays are described in U.S. Pat. Nos. 4,554,650 and 5,412,621. In locating submerged bodies, sonar is either used passively, through reception of signals sent through water by the target, or actively wherein a pulse of sound is sent into the water by a
15 sonar projector. The sound is then reflected back from the target and detected by the hydrophone arrays as an echo. This echo is received as acoustic energy by an acoustic transducer, converted into electrical energy, and read by a computer on the vessel to determine the location of objects within the water. As shown in U.S. Pat. No. 5,844,860, elongated, hose-like towed arrays of hydrophones attached to
20 the rear end of towed bodies are commonly used for the acoustic sensing of moving objects within the ocean.

In a conventional towed array, the mechanical design of the array limits the array's performance in that both the highest frequency and the lowest frequency
25 that the array can effectively process are determined by the mechanical design itself. The lowest frequency (f_L) is determined by the total array length. The f_L is the frequency with half-wavelength ($\lambda/2$) equal to the length of the acoustically active portion of the array. The highest effective frequency (f_H) is determined by

the spacing between the individual hydrophones. The f_H is the frequency with half-wavelength ($\lambda/2$) equal to the spacing between the hydrophones or hydrophone cluster.

- 5 Changes in the array performance, in either the high frequency or the low frequency, require redesigning and remanufacturing of an array which is either longer, to achieve a lower f_L , or which has reduced hydrophone spacing, to raise f_H . However, solving these problems by merely changing the length of the array or the hydrophone spacing may have consequences which may be undesirable.
- 10 For instance, raising f_H by reduction in hydrophone spacing increases the array's weight, thus complicating ballasting and buoyancy of the array and increasing the cost. Further, f_H cannot be raised above the limit determined by the physical size of the hydrophone clusters being used. In addition, lowering f_L requires that the acoustically active portion of the array be lengthened, increasing the complexity
- 15 of the stowing and handling equipment as well as limiting the maneuverability of the towing platform.

Accordingly, the present invention solves the above mentioned problems by providing a method to process the received waveforms over a particular period of

20 time in such a manner that the array performs as if it were synthetically longer or as if the hydrophone spacing were made synthetically shorter, thus synthetically raising the high frequency limit. The telemetry sampling frequency (f_s) is chosen based on sampling requirements for the highest effective received frequency f_H . Typically f_s is fixed at a multiple of f_H such that the desired signal waveform is

25 adequately represented by the sample.

SUMMARY OF THE INVENTION

- The invention provides a method for processing sonar information from an underwater hydrophone array, which array has a known spacing between adjacent hydrophones, at frequencies having wavelengths less than two times a spacing between adjacent hydrophones, the method comprising:
- a) providing an underwater hydrophone array comprising a plurality of receiver hydrophones, which array has a known length and known spacing between adjacent hydrophones, wherein λ_{DU} is the upper design wavelength for the design upper frequency limit f_{DU} for the array,
 - b) providing forward motion for the hydrophone array underwater with a vessel at a velocity of the hydrophone array in water V_s ;
 - c) selecting a synthetic upper frequency f_{SU} , wherein the synthetic upper frequency is equal to or greater than the frequency of a signal to be measured;
 - d) defining a synthetic hydrophone spacing Δd_{SU} , wherein the synthetic hydrophone spacing is equal to $\lambda_{SU}/2$ wherein λ_{SU} is the wavelength for the synthetic upper frequency f_{SU} for the array;
 - e) determining the time interval for the hydrophones to travel the distance of the synthetic hydrophone spacing,
 - f) calculating the number of sonar signal wavefronts predicted to be encountered by each hydrophone in the time interval for the hydrophones to travel the distance of the synthetic hydrophone spacing,

g) selecting a telemetry sampling rate for the predicted number of sonar wavefronts, wherein the telemetry sampling rate is selected such that each wavefront is sampled more than once;

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h) detecting samples of a first sonar wavefront with each of the hydrophones at a time t_0 and summing and recording the samples at time t_0 with a beamformer to provide a plurality of beam sets at a time t_0 ;

10 i) detecting samples of N subsequent sonar wavefronts with each of the hydrophones at $\geq 2N$ equally spaced times in a time interval Δt ; summing and recording the samples from each of the hydrophones with a beamformer to provide beam sets for the number of samples taken in the time interval Δt ; and

15 j) combining the beam sets into an assembly of beams at a time $t_1 = t_0 + \Delta t$.

The invention also provides a system for processing sonar information from an underwater hydrophone array, which array has a known spacing between adjacent hydrophones, at frequencies having wavelengths less than two times a spacing
20 between adjacent hydrophones, comprising:

a) an underwater hydrophone array comprising a plurality of receiver hydrophones, which array has a known length and known spacing between adjacent hydrophones, wherein λ_{DU} is the upper design wavelength for the design upper frequency limit f_{DU} for the array,

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b) a driver for providing forward motion for the hydrophone array underwater at a velocity of the hydrophone array in water V_s ;

c) an arrangement for selecting a synthetic upper frequency f_{SU} , wherein the synthetic upper frequency is equal to or greater than the frequency of a signal to be measured;

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d) an instrumentality for defining a synthetic hydrophone spacing Δd_{SU} , wherein the synthetic hydrophone spacing is equal to $\lambda_{SU}/2$ wherein λ_{SU} is the wavelength for the synthetic upper frequency f_{SU} for the array;

10 e) an implement for determining the time interval for the hydrophones to travel the distance of the synthetic hydrophone spacing,

f) a calculator for calculating the number of sonar signal wavefronts predicted to be encountered by each hydrophone in the time interval for the hydrophones to travel the distance of the synthetic hydrophone spacing,

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g) a sampler for selecting a telemetry sampling rate for the predicted number of sonar wavefronts, wherein the telemetry sampling rate is selected such that each wavefront is sampled more than once;

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h) a detector for detecting samples of a first sonar wavefront with each of the hydrophones at a time t_0 and summing and recording the samples at time t_0 with a beamformer to provide a plurality of beam sets at a time t_0 ; and for detecting samples of N subsequent sonar wavefronts with each of the hydrophones at $\geq 2N$ equally spaced times in a time interval Δt ; and for summing and recording the samples from each of the hydrophones with a beamformer to provide beam sets for the number of samples taken in the time interval Δt ; and

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i) a combiner for combining the beam sets into an assembly of beams at a time $t_1 = t_0 + \Delta t$.

BRIEF DESCRIPTION OF THE DRAWINGS

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Fig. 1 schematically shows a towed array of hydrophones K_1, K_2, K_3, K_4 and an incident wavefront at angle with the array θ .

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Fig. 2 shows a polar plot of the resulting beam set for a sonar wave front arriving from the 180 degree position according to Example 1.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

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According to the present invention, a computer is input with a selected high frequency limit f_H . The high frequency limit is determined by the upper limit of the frequency range that contains the signal of interest. Thus, if the signal of interest is bounded by the interval of 1 kHz to 6 kHz, 6 kHz might be selected as the high frequency limit f_H . No mechanical design parameter, such as hydrophone spacing, is used in selecting f_H since f_H is an operational parameter rather than a design parameter. It may be changed at any time in response to changing requirements.

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The speed of sound through water L_S is sampled and input into a computer. Likewise, the velocity of the array through the water V_S is sampled and input into the computer. V_S is a vector quantity so that a magnitude and direction are input to adequately define it.

With f_H selected and L_S measured, the half wavelength $\lambda/2$ can be calculated. The distance $\lambda/2$ is the maximum distance between samples that will adequately replicate the incoming waveform. Set $f_{su} = f_h$.

- 5 The time interval Δt that the individual hydrophone takes to “sweep out” the distance $\lambda/2$ is calculated using the array’s measured velocity V_S . The time interval Δt is subdivided into N intervals where N is the number of wave fronts of frequency f_H that the hydrophone encounters over the time interval Δt .
- 10 The telemetry sampling frequency f_s is set to at least twice the high frequency limit f_H such that data is sampled as each wave front encounters the hydrophone. Since the hydrophone has moved the distance $(\Delta t * V_S)/N$, the sampling frequency f_s is set in this manner so that two things are accomplished. First, each waveform is sampled more than once as it passes the hydrophone. This allows rejection of
- 15 non-coherent noise in subsequent processing of the synthetic waveform when the waveforms are combined over the interval Δt . Second, since the hydrophone movement between samples is proportionate to the wavelength for f_H , the coherent signal waveform is sampled N times over the distance $\lambda/2$. Thus the synthetic waveform is described at N points along the interval $(0, \lambda/2)$.
- 20 At the beginning t_0 of each interval Δt , a sample is taken at each hydrophone in the array. The samples are summed in a beamformer to provide a composite family of output signals (beam sets). These beam sets are recorded and stored. The process is repeated N equally spaced times. At the completion of N samples
- 25 over the time interval Δt , the array has traveled $\lambda/2$ distance from the initial point. The database contains N families of beam sets, one from each of the N sample periods along the interval.

A transpositional function is applied to each of the N beam sets that “moves” it forward to position $\lambda/2$ and time $t_1 = t_0 + \Delta t$. The transposed data is combined so that all the beam sets taken over the interval are combined into one data family
5 composed of beams that are synthesized at time Δt .

The transposed signals constitute a synthesized waveform made up of the N waveforms sampled at each time over the interval Δt . The output is a single synthesized waveform that would appear like a single wave front encountered at
10 position $0 + \lambda/2$ and at time t_1 . Only coherent signal that was present in each wave front encountered in each of the N samples would be present in the synthetic wave front. Non-coherent signal (noise), since by its non-coherent nature only appears in one of the N samples, does not appear in the synthetic waveform. Thus the signal to noise ratio SNR of the synthetic signal is improved over the natural
15 signal.

One application of this method and system might be for a towed array used to detect a submerged submarine. As an example, if the particular towed array is built with a mechanical upper frequency of 1 kHz (hydrophone spacing of 2.4 ft)
20 is to be used to search for a submarine that emanates a signal in the range of 1 to 4 kHz, the upper frequency would be selected to cover the frequency band of interest by first selecting an f_H of 4 kHz. The speed of sound in the water L_S is measured as 4800 ft/sec and array velocity V_S is measured at 5 knots in a direction of North. The half wavelength $\lambda/2$ is calculated as 0.6 ft. N is thus 480
25 and the time interval Δt is 0.0718 sec. The distance 0.6 ft and time 0.0718 sec are divided into 480 separate, equal intervals with a sample point at the beginning of each interval. Signal data is collected at each sample point, processed through a

beamformer, and transposed to a position 0.6 ft from the start point and 0.0718 seconds from the start time. The synthetic waveform is assembled at that point and analyzed for signals of interest.

5 The Theory

The array movement is used to “sweep out” the interval spacing between hydrophones, thus synthesizing a higher hydrophone density and closer hydrophone spacing. Since the array hardware upper design frequency f_{DU} for a particular towed array is based on having the hydrophone spacing equal to the
10 half wavelength $\lambda_{DU}/2$ for that f_{DU} , the concept of synthetically generating hydrophone density raises the upper frequency limit for the array above the mechanical design limit.

If an array is designed with hydrophone spacing Δd_{DU} , then the conventional array
15 hardware upper design frequency f_{DU} would satisfy the equation:

$$f_{DU} = L_S / \Delta d_{DU}$$

wherein: L_S = the speed of sound in water

$$\Delta d_{DU} = \lambda_{DU} / 2$$

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The sampling frequency f_S is a multiple of f_{DU} , and selected so that adequate data is sampled. A number of 2.5 times f_{DU} is a typical value. With the conventional approach, raising f_{DU} entails lowering Δd_{DU} , i.e. adding hydrophones to the array. For a given array length, doubling the upper design frequency f_{DU} requires
25 halving the hydrophone spacing Δd_{DU} , thus doubling the hydrophone population.

Likewise, since the design frequency f_{DU} doubled, the sampling frequency f_s would also require doubling, usually entailing a change to the telemetry system.

The array's movement through the water is utilized to sample data at discrete intervals. The data is processed by standard beamforming techniques and "transposed" by mathematical means such that the all samples are taken over the interval Δt , where Δt is defined by the interval t_0 to t_1 , is transposed to time t_1 . Careful selection of the discrete interval allows the increase in the subsequent synthetic upper frequency f_{SU} by an integer multiple of the array hardware design upper frequency f_{DU} , such that:

$$f_{SU} = A * f_{DU} \quad \text{where } A = \text{the desired integer multiple}$$

Referring to Fig. 1, there is shown a towed array of hydrophones K_1, K_2, K_3, K_4 and an incident wavefront at angle with the array θ .

The f_{SU} is a function of the hydrophone spacing Δd_{HU} , array velocity V_s , and the incident angle of the wavefront with the array θ .

wherein: L_s = speed of sound in water

V_s = towed array velocity

θ = incident angle of wave front

K_N = hydrophone at position N

Δd_{HU} = design hydrophone spacing = $\lambda_{FU}/2$ for f_{DU}

$\lambda_{SU}/2$ = half wavelength for synthetic upper frequency f_{SU}

If we define a synthetic hydrophone spacing Δd_{SU} such that Δd_{SU} is equal to $\lambda_{SU}/2$ for f_{SU} , then: $\Delta d_{SU} = V_s \Delta t$ where Δt is the time interval for the hydrophone to

travel the distance Δd_{SU} . Since $\Delta d_{SU} = \lambda_{SU}/2$ where $\lambda_{SU}/2$ is the half wavelength for the synthetic upper frequency, then $\Delta t = \lambda_{SU}/(2 V_S)$.

In the time interval Δt , the number of wave fronts passing the hydrophone K_N as the hydrophone travels from position X_0 to position $X_{\lambda/2}$ at speed V_S , would be

5 defined by:

$$L_S \cos \theta = (N_X \lambda_{SU} + \lambda_{SU}/2) / \Delta t$$

wherein N_X = integer number of wave fronts passing hydrophone K_N in time Δt .

$$L_S \cos \theta = [\lambda_{SU}/2 (2N_X + 1)] / [\lambda_{SU}/(2 V_S)]$$

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$$2N_X + 1 = L_S \cos \theta / V_S$$

$$\text{Thus: } N_X = \frac{1}{2} [(L_S \cos \theta / V_S) - 1]$$

Hydrophone K_N would sample the wave train at the $\lambda_{SU}/2$ position on the N^{th} wave of the train. Using conventional sampling theory, $f_{SH} = f_{SU}/N$, a very small number of samples would be taken. But, if samples are taken at each N_X over the

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interval $t = (0, \Delta t)$ then $f_{SH} = f_{SU}$ where f_{SH} is a highly over-sampled space such that each wave form is sampled as it passes the hydrophone K_X at the position

$X_n = n \Delta d_{SU} / N$. Thus the wave train is sampled sequentially such that each

subsequent wave in the train is sampled at a position over the interval $(0, \lambda_{SU}/2)$

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such that $X_n = n \lambda_{SU} / 2N$.

The conventional time domain beamforming equation can be written as:

$$A_r(t) = \sum_{K=0}^{K=Z-1} W_K f_K(t + \tau_{K,r})$$

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wherein: Z = the number of hydrophones in the array

W_K = shading factor

$\tau_{K,r}$ = time delay applied to the K^{th} element data for the r^{th} beam

With synthetic beamforming, the beamforming at each position X_N would be:

$$A_r(t) = \sum_{K=0}^{K=Z-1} W_K f_K(t + \tau_{K,r,X})$$

wherein: $\tau_{K,r,X}$ = time delay applied to the K^{th} element data for the r^{th} beam at position X_N .

Over the sampling time interval $(0, \Delta t)$, this results in a family of N beam sets, with each set identified with a particular time t_n and position X_n that is contained within the intervals $(0, \Delta t)$ and interval $(0, \lambda_{SU}/2)$. The beam sets are then transposed such that the composite beam set is formed at position X_N and at time Δt . Thus, the composite time domain beamforming equation takes the form:

$$A_r(t) = \sum_{X=0}^{X=N} f_X(\psi_{K,r,X}) \sum_{K=0}^{K=Z-1} W_K f_K(t + \tau_{K,r,X})$$

Where: $\psi_{K,r,X}$ = transpositional function applied to the K^{th} element data for the r^{th} beam at the X^{th} position.

The system according to the invention comprises the underwater hydrophone array which is known in the art. The hydrophones of the array may be individual hydrophones or may be clusters of hydrophones. Hydrophone clusters may be arranged linearly or grouped in various geometric arrangements such as spherical, planar, conformal to the vessel. The hydrophone spacings for purposes of this invention are measured from the midpoint of one hydrophone cluster to the midpoint of the adjacent hydrophone cluster. The system includes a driver for providing forward motion for the hydrophone array underwater. The driver is typically a surface ship or a submarine. The array may be attached to the outer surface of the hull of the vessel, or it may be towed directly by the vessel, or it may be towed by the vessel via an intermediate platform. The system then includes an arrangement for selecting a synthetic upper frequency. Typically,

such an arrangement comprises a determination of the bounds of the frequency of the sonar signal to be measured. These bounds are usually known to those skilled in the art. The synthetic upper frequency is selected to be equal to or greater than the upper bounds of the sonar signal to be measured by means of either manual
5 input or by means of a computer algorithm.

The system then includes an instrumentality for defining a synthetic hydrophone spacing. Typically, such an instrumentality comprises a computer algorithm that takes input of the synthetic upper frequency and calculates the half wavelength for
10 that frequency. The algorithm then sets the synthetic hydrophone spacing equal to the half wavelength.

The system then includes an implement for determining the time interval for the hydrophones to travel the distance of the synthetic hydrophone spacing.
15 Typically, such an implement comprises a computer algorithm that takes as input the synthetic hydrophone spacing and a physical means for measuring the array velocity through the water. The computer algorithm calculates the time interval for the hydrophone to travel the synthetic hydrophone spacing.

20 The system then includes a calculator for calculating the number of sonar signal wavefronts predicted to be encountered by each hydrophone in the time interval for the hydrophones to travel the distance of the synthetic hydrophone spacing. Typically, such a calculator comprises a computer algorithm that calculates the number of wavefronts encountered by the hydrophone during the time interval for
25 each of a family of expected incident angles θ .

The system then includes a sampler for selecting a telemetry sampling rate for the predicted number of sonar wavefronts. Typically, such a sampler comprises a

computer algorithm that takes as input the number of expected sonar signal wavefronts for the case of the limiting incident angle θ . The computer algorithm also takes as input the number of samples per wavefront that has been chosen. The algorithm calculates the sample rate and outputs that value to the control
5 function for the telemetry to sample the sonar signal.

The system then includes a detector for detecting samples of a sonar wavefront with each of the hydrophones and summing and recording the samples with a beamformer to provide beam sets. Typically, such a detector comprises a plurality
10 of hydrophones that convert the sonar signal to electrical energy. The telemetry system samples the electrical energy at discrete times. The samples are combined and transformed in the beamformer.

The system then includes a combiner for combining the beam sets into an
15 assembly of beams. Typically, such a combiner comprises a computer algorithm that calculates the transformation and transposition functions to combine the beams formed during the time interval Δt at time t_1 in position Δt_{SU} .

The following non-limiting examples serve to illustrate the invention. It will be
20 appreciated that variations in proportions and alternatives in elements of the components of the invention will be apparent to those skilled in the art and are within the scope of the present invention.

EXAMPLE 1

25 This examples illustrates a method for determining a variable sample rate, dependent on array velocity and selected upper synthetic frequency. An upper

synthetic frequency is chosen and a synthetic hydrophone spacing is calculated. The array velocity is used to calculate a time period needed for the hydrophone to travel the synthetic hydrophone distance. The number of sonar wave fronts encountered by the hydrophone during the time period is calculated. The sample rate is then calculated based on the number of wave fronts and the time period. A linear array is built with eight hydrophone groups equally spaced such that the array is 10.5 meters in length. The array is designed with a spacing between hydrophones of 1.5 meters. Since the upper design frequency $F_{DU} = L_S / \Delta d_{DU}$ and the speed of sound through the water L_S equals 1500 meters/sec, then F_{DU} equals 500 Hz.

The sonar signal to be measured is in the range of 500 to 1000 Hz. To raise the frequency capability of this array to 1000 Hz, select a synthetic upper frequency equal to two times the f_{DU} . $f_{SU} = A * f_{DU}$ with $A=2$. The synthetic hydrophone spacing Δd_{SU} is set equal to the half wavelength $\lambda/2$ for F_{SU} . $\lambda/2 = L_S / F_{SU}$ so $\lambda/2$ and Δd_{SU} are equal to 0.75 meters.

If the array is moved through the water at 10 knots (5.14 meters/sec) and $\Delta d_{SU} = V_S \Delta t$ then the time for a hydrophone to move from its position at time t_0 a distance equal to Δd_{SU} is $\Delta t = 0.1459$ seconds. To determine the number of wave fronts N the hydrophone will encounter over the time interval Δt , the equation $N = \frac{1}{2}[(L_S \cos \theta / V_S) - 1]$ is solved for $\cos \theta = 1$, the limiting case. $N = 145$ wave fronts encountered. The sample rate SR is then $2N / \Delta t = 1994$ samples per second. A transpositional function is applied to each of the beam sets that “moves” it forward to position $\lambda/2$ and time Δt . The transposed data is combined so that all the beam sets taken over the interval are combined into one data family composed

of beams that are synthesized at time Δt . Fig. 2 shows a polar plot of the resulting beam set for a sonar wave front arriving from the 180 degree position.

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EXAMPLE 2

In this example, a synthetic upper frequency of four times the design upper frequency is chosen. A linear array is built with hydrophone groups equally spaced such that the array is 105 meters in length. The array is designed with a spacing between hydrophone of 15 meters. Since the upper design frequency $f_{DU} = L_S / \Delta d_{DU}$ and the speed of sound through the water L_S equals 1500 meters/sec, then f_{DU} equals 50 Hz. The sonar signal to be measured is in the range of 150 to 200 Hz. To raise the frequency capability of this array to 200 Hz, select a synthetic upper frequency equal to two times the f_{DU} . $f_{SU} = A * F_{DU}$ with $A=4$. The synthetic hydrophone spacing Δd_{SU} is set equal to the half wavelength $\lambda/2$ for f_{SU} . $\lambda/2 = L_S / 2 F_{SU}$ so $\lambda/2$ and Δd_{SU} are equal to 3.75 meters. If the array is moved through the water at 15 knots (7.71 meters/sec) and $\Delta d_{SU} = V_S \Delta t$ then the time for a hydrophone to move from its position at time t_0 a distance equal to Δd_{SU} is $\Delta t = 0.486$ seconds. To determine the number of wave fronts N the hydrophone will encounter over the time interval Δt , the equation $N = \frac{1}{2}[(L_S \cos \theta / V_S) - 1]$ is solved for $\cos \theta = 1$, the limiting case. $N = 97$ wave fronts encountered. The sample rate SR is then $2N / \Delta t = 398.2$ samples per second. A transpositiona function is applied to each of the beam sets that “moves” it forward to position $\lambda/2$ and time Δt . The transposed data is combined so that all the beam sets taken over the interval are combined into one data family composed of beams that are synthesized at time Δt . A polar plot of the resulting beam set for a sonar wave front arriving from the 180 degree position is similar to that of Fig. 2.

EXAMPLE 3

A method for using a fixed sample rate is shown. An upper synthetic frequency is
5 chosen and a synthetic hydrophone spacing is calculated. The array velocity is
used to calculate a time period needed for the hydrophone to travel the synthetic
hydrophone distance. The sample point nearest the synthetic hydrophone point is
chosen and the distance between the two is calculated. An error function is
calculated and applied to the sonar signal. A linear array is built with eight
10 hydrophone groups equally spaced such that the array is 10.5 meters in length.
The array is designed with a spacing between hydrophone groups of 1.5 meters.
Since the upper design frequency $f_{DU} = L_s / \Delta d_{DU}$ and the speed of sound through
the water L_s equals 1500 meters/sec, then f_{DU} equals 500 Hz. The system has a
sample rate of 3,000 samples per second. The sonar signal to be measured is in
15 the range of 500 to 1000 Hz. To raise the frequency capability of this array to
1000 Hz, select a synthetic upper frequency equal to two times the f_{DU} . $f_{SU} = A * f_{DU}$
with $A=2$. The synthetic hydrophone spacing Δd_{SU} is set equal to the half
wavelength $\lambda/2$ for f_{SU} . $\lambda/2 = L_s / 2 f_{SU}$ so $\lambda/2$ and Δd_{SU} are equal to 0.75 meters.
If the array has a velocity V_s through the water of 10 knots (5.14 meters/sec) and
20 $\Delta d_{SU} = V_s \Delta t$ then the time for a hydrophone to move from its position at time t_0 a
distance equal to Δd_{SU} is $\Delta t = 0.1459$ seconds. The number of samples available
during the time period that the hydrophone travels the synthetic hydrophone
distance Δd_{SU} , given that $SR=3000$, is equal to the sample rate times Δt . Thus
 $N = \text{round}(SR * \Delta t) = 437$. The sample taken nearest the synthetic hydrophone
25 point is taken at a distance from the origin equal to $(NS * V_s) / SR = 0.7493$ meters.
Thus there is a 0.0007 meter error between the sample point and the synthetic
hydrophone distance. The time difference between the two positions $1.36 * 10^{-5}$

is applied as an error correction. The correction factor is a positive value if the sample point is less than synthetic hydrophone point or negative if the sample point is greater than the synthetic hydrophone point.

- 5 This method further allows for corrections for measured speed. Assume that the actual array velocity V_A through the water is 9 knots (4.63 meters/second) when the measured velocity V_S is 10 knots. The sample taken nearest the synthetic hydrophone point is taken at a distance from the origin equal to $(NS * V_A)/SR = 0.6751$ meters. Thus there is a 0.0749 meter error between the sample point and
- 10 the synthetic hydrophone distance. The time difference between the two positions $1.62 * 10^{-2}$ is applied as an error correction.

- A transpositional function is applied to each of the beam sets that “moves” it forward to position $\lambda/2$ and time Δt . The transposed data is combined so that all
- 15 the beam sets taken over the interval are combined into one data family composed of beams that are synthesized at time Δt . A polar plot of the resulting beam set for a sonar wave front arriving from the 180 degree position is similar to Fig. 2.

- While the present invention has been particularly shown and described with
- 20 reference to preferred embodiments, it will be readily appreciated by those of ordinary skill in the art that various changes and modifications may be made without departing from the spirit and scope of the invention. It is intended that the claims be interpreted to cover the disclosed embodiment, those alternatives which have been discussed above and all equivalents thereto.

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